Development of a Reference Governor-based Control Scheme for Integrated Energy Systems

Integrated Energy Systems: Analysis of Technical & Economic Issues

Nuclear Science and Engineering Division

About Argonne National Laboratory

Argonne is a U.S. Department of Energy laboratory managed by UChicago Argonne, LLC under contract DE-AC02-06CH11357. The Laboratory's main facility is outside Chicago, at 9700 South Cass Avenue, Argonne, Illinois 60439. For information about Argonne and its pioneering science and technology programs, see www.anl.gov.

Document availability

Online Access: U.S. Department of Energy (DOE) reports produced after 1991 and a growing number of pre-1991 documents are available free at OSTI.GOV (<http://www.osti.gov/>), a service of the U.S. Dept. of Energy's Office of Scientific and Technical Information

Reports not in digital format may be purchased by the public from the National Technical Information Service (NTIS):

U.S. Department of Commerce
National Technical Information Service
5301 Shawnee Rd
Alexandria, VA 22312
www.ntis.gov
Phone: (800) 553-NTIS (6847) or (703) 605-6000
Fax: (703) 605-6900
Email: **orders@ntis.gov**

Reports not in digital format are available to DOE and DOE contractors from the Office of Scientific and Technical Information (OSTI):

U.S. Department of Energy
Office of Scientific and Technical Information
P.O. Box 62
Oak Ridge, TN 37831-0062
www.osti.gov
Phone: (865) 576-8401
Fax: (865) 576-5728
Email: **reports@osti.gov**

Disclaimer

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor UChicago Argonne, LLC, nor any of their employees or officers, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of document authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof, Argonne National Laboratory, or UChicago Argonne, LLC.

Development of a Reference Governor-based Control Scheme for Integrated Energy Systems

Integrated Energy Systems: Analysis of Technical & Economic Issues

prepared by
Roberto Ponciroli, Giovanni Maronati and Richard B. Vilim

Nuclear Science and Engineering Division, Argonne National Laboratory

July 31, 2019

ABSTRACT

The concept of an Integrated Energy System (IES) is meant to combine different energy technologies in synergistic ways to achieve a more secure and economical energy supply. The RAVEN-based HYBRID framework is used to find the optimal installed capacity and the optimal economical dispatch of each component of the IES. In practice what is achievable is limited by not only the inherent physical response characteristics of individual plant units but also by equipment operating limits. The inherent response characteristics are presently accounted for in the RAVEN-based HYBRID framework by dynamic models for plant units. The equipment operating limits, which are not yet addressed in HYBRID, are the subject of this report. These limits are set to achieve a design service life for a plant unit and are based on material degradation in the presence of mechanical fatigue induced by thermal cycling and by structure creep resulting from elevated temperature conditions.

In general, the plant unit designer determines and specifies the allowable operating range of key process variables. It is then up to the integrated system design engineer to ensure those conditions are met. This can be accomplished through a combination of limiting the demand rates made on the plant unit and designing a control system that limits variations of key process variables. The typical control system design procedure, however, is not well suited for achieving this for complex dynamic systems such as encountered in integrated energy systems where multiple plant units must be simultaneously coordinated.

This report describes how equipment operating limitations in an IES can be formally met through a control system design procedure known as the Reference Governor. The approach augments the existing controllers in a plant unit with an advance controller that modifies the issued set-points so that selected process variables remain within limits. The design procedure is applied to the reference multi-unit system that has been the focus of Modeling and Simulation task in the Integrated Energy System program. Results describing application to the problem of limiting key process variables during operational transients for two of the plant units, the balance of plant and the gas turbine, are then presented. It is demonstrated that the Reference Governor method is an effective means for ensuring equipment operating constraints can be met in an IES. The software that implements the method has been made accessible to others on the Modeling and Simulation upload site.

TABLE OF CONTENTS

ABSTRACT	1
TABLE OF CONTENTS	3
LIST OF FIGURES	4
LIST OF TABLES	5
1 INTRODUCTION	6
2 REFERENCE GOVERNOR CONCEPT	7
3 ADVANTAGES OF ADDING THE RG LAYER.....	8
4 IMPLEMENTATION OF THE RG-BASED CONTROL SCHEME.....	8
5 SECONDARY ENERGY SYSTEM (SES).....	10
5.1. Definition of process variable constraints	10
5.2. Open-loop configuration.....	11
5.3. Closed-loop configuration	11
5.4. Design of a dedicated State Observer: Kalman filter	13
5.5. Results.....	15
5.5.1. Imposed output variables constraints	15
5.5.2. Simulation outcomes	16
6 BALANCE OF PLANT (BOP)	17
6.1. Definition of process variable constraints	17
6.2. Open-loop configuration.....	18
6.3. Closed-loop configuration	18
6.4. Derivation of the state-space representation matrices	21
6.5. Results.....	23
6.5.1. Imposed output variables constraints	23
6.5.2. Simulation outcomes.....	23
7 HIGH-TEMPERATURE STEAM ELECTROLYSIS PLANT (HTSE)	25
7.1. Description of the plant configuration.....	25
7.2. Imposed variable constraints	29
7.3. Open-loop configuration.....	29
8 CONCLUSIONS.....	31
9 NOMENCLATURE.....	31
10 REFERENCES.....	32

LIST OF FIGURES

Figure 1-1. Current architecture of the RAVEN/Dymola coupling.....	6
Figure 2-1. RG scheme applied to closed-loop (Plant + Controller) system subject to constraints [4].	8
Figure 3-1. Proposed RG-based architecture for the RAVEN/Dymola coupling.....	8
Figure 5-1. Graphical interface of the Dymola model of the SES unit (<i>open loop</i> configuration).11	
Figure 5-2. Graphical interface of the Dymola model of the SES unit and PI controller (<i>closed loop</i> configuration).....	12
Figure 5-3. Representation of poles and zeros for the LTI discrete time closed-loop system (SES + controller).....	13
Figure 5-4. Final configuration of the closed-loop system (“SES”) coupled with the Kalman filter and the RG block (“Ref Gov”).....	14
Figure 5-5. Graphical representation of the Kalman filter concept.	15
Figure 5-6. Closed-loop power response (ramp set-point signal).	16
Figure 5-7. Closed-loop power response (saw-tooth set-point signal).	16
Figure 5-8. Closed-loop temperature response (saw-tooth set-point signal).	17
Figure 6-1. Graphical representation of the Dymola model of the EM coupled with the BOP system (<i>open loop</i> configuration).....	18
Figure 6-2. Graphical representation of the Dymola model of the EM coupled with the BOP and the corresponding control system (<i>closed loop</i> configuration).	19
Figure 6-3. Final configuration of the closed-loop system (“EM+BOP”) coupled with the Kalman filter and the RG block (“Ref Gov”).....	19
Figure 6-4. Simulation outcomes of the performed operational transient.	20
Figure 6-5. Representation of poles and zeros for the LTI discrete time closed-loop system (BOP + EM + controller).	22
Figure 6-6. Results of the performed system identification. The solid blue curves represent the LTI model responses, the dashed red lines the Dymola model ones.	23
Figure 6-7. Operational transient. The most constraining limit is the imposed on the electrical power output (y1).	24
Figure 6-8. Operational transient. The most constraining limit is the imposed on the turbine inlet pressure (y2).	25
Figure 7-1. Graphical representation of the BOP and IP power consumptions.....	26
Figure 7-2. Dymola model of the HTSE plant. Pairings among input and output variables are represented (“Power control” strategy).	27
Figure 7-3. Dymola model of the HTSE plant. Pairings among input and output variables are represented (“Steam flow control” strategy).	27
Figure 7-4. Dymola model of the SOEC stack.	28
Figure 7-5. Step response. Power consumption of the HTSE plant (a); Electrolyzer solid structure temperature gradient (b); SU factor (c).	30
Figure 7-6. Saw-tooth response (5 min period). Power consumption of the HTSE plant (a); Electrolyzer solid structure temperature gradient (b); SU factor (c).	30
Figure 7-7. Saw-tooth response (10 min period). Power consumption of the HTSE plant (a); Electrolyzer solid structure temperature gradient (b); SU factor (c).	31

LIST OF TABLES

Table 5-1 – SES constrained process variables.....	11
Table 6-1 – BOP constrained process variables.....	17
Table 7-1 – HTSE control scheme components (derived from [17][18]).....	28
Table 7-2 – HTSE constrained process variables.	29

1 INTRODUCTION

The concept of Integrated Energy Systems (IES) is meant to combine different energy technologies in synergistic ways to achieve a more secure and economical energy supply. The RAVEN-based HYBRID framework is used to find the optimal installed capacity and the optimal economical dispatch of each component of the IES. HYBRID solves the coupled capacity planning and economical dispatch optimization problem with the objective of minimizing the Levelized Cost of Electricity (LCOE).

To account for the time-dependent dynamics of each subsystem, the HYBRID framework includes a Dymola object-oriented model of the process dynamics. The optimization algorithm evaluates the power dispatched by the single unit components, i.e., P_{SES} , P_{ES} , P_{BOP} , P_{PHS} , along the considered time horizon, e.g., a day, a week or two weeks. The architecture as implemented in this report is graphically represented in Figure 1-1 by the shaded region. RAVEN-provided trajectories ($r(t)$) are fed to the Dymola model. They constitute the set-points for feedback controllers (PIDs). These PIDs along with the associated control system saturation elements related saturation effects will perform the necessary control actions ($u(t)$) to get the IES system to evolve accordingly, i.e. the regulators will adjust the system inputs so that the system (a single unit component) power outputs ($y(t)$) can meet the imposed set-point trajectories.

Figure 1-1. Current architecture of the RAVEN/Dymola coupling.

In the operation of a power plant, the physical constraints affecting the components and their effect during operational transients need to be taken into account. For example, in the operation of the gas turbine (SES), the temperature of the exhaust gases at the combustion chamber outlet needs to be carefully controlled. Though this temperature is related to the thermal efficiency of the Brayton cycle, if its value gets too high, it will compromise the overall durability of the mechanical components in gas turbine engines. Specifically, engineers are concerned with material stresses, fatigue life, and radial growth of turbine disks [1]. For these reasons, strict temperature limits need to be respected during the turbine operation.

The existing optimization algorithm in HYBRID evaluates the optimal power set-points that meet the limits on the maximum/minimum power bounds for a component, but the algorithm does not ensure the safety-limits on temperature field are respected. An additional layer is needed to smooth those control actions that would otherwise be too aggressive and result in temperature limits being

violated. In the currently implemented control scheme configuration, *ad hoc* heuristic solutions are adopted, i.e. dedicated filter limits the instantaneous values (Eq. (1)) assumed by the control actions performed by the actuators and/or ramp limiters (Eq. (2)) saturate abrupt variations. In this way, the PIDs-estimated control actions ($\tilde{u}(t)$) are smoothed so that the ones actually performed on the system ($u(t)$) will not cause the process variables to exceed the corresponding safety limits.

$$u_{min} \leq u(t) \leq u_{max} \quad (1)$$

$$\left(\frac{du}{dt}\right)_{min} \leq \frac{du}{dt} \leq \left(\frac{du}{dt}\right)_{max} \quad (2)$$

In the currently implemented control scheme configuration, the upper and the lower bounds of the performed control actions and the corresponding rates of variation, i.e. u_{min} , u_{max} , $\left(\frac{du}{dt}\right)_{min}$, $\left(\frac{du}{dt}\right)_{max}$, either are obtained from literature or from performed simulations. On the other hand, during unprecedented operational transients, the control system can fail at meeting the process variable constraints. Alternatively, the imposed limits can be too conservative and, in that case, poor dynamic performance will be observed. To avoid these situations, a different approach is proposed, i.e. a model-based controller that allows instantaneously adjusting the actuator limits according to the estimated state of the controlled process.

2 REFERENCE GOVERNOR CONCEPT

The reference governor (RG) is an add-on scheme for enforcing pointwise-in-time state and control constraints by modifying the reference command to a well-designed (for small signals) closed-loop system [2][3][4]. The intent of the RG is to preserve, whenever possible, the response of the closed loop system designed by conventional control techniques. This result is achieved by ensuring that the modified reference command is as close as possible to the original reference command subject to satisfy certain user-defined constraints, which might allow meeting limits on thermo-mechanical stresses, power ramps, etc. [4]. We assume that a primal controller has already been designed to stabilize the system and provide good tracking properties in the absence of constraints, while the constraint fulfillment task is left to the RG. Commonly adopted controllers provide the system with asymptotic stability, acceptable dynamic performance, and robustness towards disturbances, but they cannot explicitly consider the presence of constraints on the operating condition of the component [4]. Unlike this approach which attempts to solve stabilization, tracking, and constraints fulfillment at the same time, the RG-based control scheme is based on a two-step approach [4]. First, a primary compensated controller is designed to stabilize the system and provide satisfactory tracking capabilities in the absence of constraints. Then, the RG block is added to enforce user-specified constraints. As shown in Figure 2-1, it plays the role of a pre-filter that, based on the current value of the desired reference command ($r(t)$) and of the state estimate ($x(t)$), generates a modified reference command that is supplied to the primal control system ($v(t)$) [4].

[Figure withheld. Inquiries should be directed to the authors]

Figure 2-1. RG scheme applied to closed-loop (Plant + Controller) system subject to constraints [2].

3 ADVANTAGES OF ADDING THE RG LAYER

In Figure 3-1, the proposed control system architecture for implementation of the RG scheme is shown. In this configuration, the RAVEN-provided set-points ($r(t)$) constitute the input of the RG block. The output of the RG is the adjusted version of the set-points ($v(t)$) which are compliant with the system constraints. These trajectories are then fed to the PID controllers, which eventually will perform the estimated control actions ($u(t)$) on the system.

Figure 3-1. Proposed RG-based architecture for the RAVEN/Dymola coupling.

The added RG-based layer ensures that the imposed set-points will not lead to violations of the constraints to be imposed on the main process variables. In addition, since this layer takes care of these constraints, the saturation elements limiting the PID control actions are no longer required and can be removed from the control scheme. Either you impose a saturation effect on the performed control action (Eq. (3)) or you adjust the controller set-point (Eq. (4)), the final result is the same, i.e. the perturbation performed on the dynamic system is going to be smooth

$$u(t) = K_p \cdot (y(t) - r(t)) \cdot sat \quad (3)$$

$$u(t) = K_p \cdot (y(t) - v(t)) \quad (4)$$

where *sat* is shorthand for the function that represents that saturation elements. Because of the saturation effects, in addition to the inherent system inertia, it might happen that the unit cannot meet the demanded set-point variations. As a result, missed demand scenarios are likely to occur.

4 IMPLEMENTATION OF THE RG-BASED CONTROL SCHEME

The discrete-time state model representation takes the form [4]:

$$\begin{cases} x(t+1) = Ax(t) + Bv(t) \\ y(t) = Cx(t) + Dv(t) \end{cases} \quad (5)$$

This model represents the closed-loop dynamics of the plant with a stabilizing controller. Consequently, the closed-loop system is assumed to be asymptotically stable, i.e., the matrix A is Schur (all eigenvalues are strictly in the interior of the unit disk) [2]. Constraints are imposed on the output variables $y(t) \subset \mathbb{R}^p$.

$$y(t) \in Y \text{ for all } t \in \mathbb{Z}^+ \quad (6)$$

While not required, constraints are often defined so that Y is a polytope, i.e., compact set defined by a set of linear inequalities. Note that, since Eq. (5) is a model of the closed-loop system, Eq. (6) can represent constraints on either state or control variables. In order for the reference $v(t)$ to be as close as possible to the set-point $r(t)$, the RG algorithm uses the following update [5]:

$$v(t) = v(t-1) + \beta(t)(r(t) - v(t-1)) \quad (7)$$

where $\beta(t)$ is a scalar adjustable parameter in the range $[0,1]$. If the constraints are not violated, $\beta(t) = 1$ so that $v(t) = r(t)$. If there is a potential for constraint violation, the value of $\beta(t)$ is decreased. In the extreme case, the reference governor isolates the system by setting $\beta(t) = 0$, which implies $v(t) = v(t-1)$. To assure safety, the following constraint is enforced [4]:

$$(v(t), x(t)) \in P, \quad (8)$$

where $P \subset \mathbb{R}^m \times \mathbb{R}^n$. The set O_∞ is the maximum output admissible set, i.e., the set of all states and constant inputs $\bar{v}$ such that, if $\bar{v}$ is constantly applied to the system, the response will not violate constraints for any possible realization of the disturbance $w(t+k) \in W$. The choice of $P = \tilde{O}_\infty$, where $\tilde{O}_\infty$ is a slightly tightened version of O_∞ is frequently made. It can be shown that $\tilde{O}_\infty$ is a non-empty, positively-invariant (with $v(t)$ maintained constant) and finitely-determined polytope, representable by a finite set of linear inequalities of the form [4]:

$$\tilde{O}_\infty = \{(x(0), v): H_x x(0) + H_v v \leq s\} \quad (9)$$

with $\tilde{O}_\infty$ computed off-line as in Eq. (9) and using $P = \tilde{O}_\infty$ in Eq. (8), the selection strategy for $\beta(t)$ at the time instant t consists of maximizing $\beta(t)$ subject to the following constraints [4]

$$0 \leq \beta(t) \leq 1, \quad (v(t), x(t)) \in \tilde{O}_\infty \quad (10)$$

Since only the scalar parameter $\beta(t)$ is optimized on-line, the computational complexity of this approach is very low, and the optimization problem is explicitly solvable. If the system model or the constraints change, $[H_x, H_v, s]$ can be computed on-line. If we consider the case $W = \{0\}$, $Y = \{y \in \mathbb{R}^p: Sy \leq s\}$, the condition $(v(t), x(t)) \in \tilde{O}_\infty$ reduces to [5]

$$S\left(CA^kx(t) + C(I - A)^{-1}(I - A^k)Bv(t) + Dv(t)\right) \leq s, \quad (11)$$

$$S\left(C(I - A)^{-1}Bv(t)\right) \leq s(1 - \varepsilon), \quad (12)$$

$$k = 0, \dots, k^* \quad (13)$$

where k^* is any upper bound on the finite-determination index, and $0 < \varepsilon < 1$. The conditions on $\beta(t)$ then take the form [4]:

$$\beta(t)H_v(k)(r(t) - v(t - 1)) \leq s - H_x(k)x(t) - H_v(k)v(t - 1), \quad (14)$$

$$\beta(t)H_v(\infty)(r(t) - v(t - 1)) \leq s(1 - \varepsilon) - H_v(\infty)v(t - 1), \quad (15)$$

$$k = 0, \dots, k^* \quad (16)$$

The matrices $H_v(k)$, $H_v(\infty)$ and $H_x(k)$ can be either pre-computed offline and stored or computed on-line in case the model changes. The RG algorithm can be applied to both SISO and MIMO systems, i.e. systems with multiple set-points and multiple process variables. From this standpoint, the RG algorithm was successfully applied to the flight-path control of an F-16 aircraft [5], i.e. a problem characterized by two control variables.

5 SECONDARY ENERGY SYSTEM (SES)

5.1. Definition of process variable constraints

Materials play a central role in the operation of the gas turbine, and appropriate materials choices are essential to maximizing gas turbine efficiency and operational longevity. From this standpoint, the turbine section probably represents the most challenging environment in the gas turbine. The temperature of the working fluid entering the turbine section frequently exceeds the working temperature limit of nickel-base superalloys, and in the most advanced industrial gas turbines the, gas path temperatures can exceed the melting temperature of the blade and vane alloys by several hundred Celsius degrees. Effective cooling schemes and protective thermal barrier coatings are then needed [6]. The highest firing temperature that of a commercial turbine is 1,600 °C, which is achieved by the Mitsubishi J-series turbine [7]. At the same time, too low temperatures are not welcome either. The production of carbon monoxide is fundamental in the combustion process, i.e., whenever the combustion reaction is not complete some monoxide is emitted at the turbine outlet. For a heavy-duty gas turbine, the carbon monoxide emissions increase quickly for firing temperatures below about 816 °C [8]. Therefore, in the operation of the turbine, it is fundamental to make sure that the firing temperature does not drop below 816 °C.

Gas turbines are also characterized by a minimum power load that they can sustain, also known as turndown minimum load. The minimum load for GE 7E turbines (nominal capacity 91 MW) is equal to 35% [9]. The GE 7F heavy duty gas turbine, which can operate in both simple and combined cycle, has a turndown minimum load of 27%-58%, based on the combined cycle configuration [10]. The GE 9HA turbines are the largest heavy-duty gas turbines on the market. 9HA.02 configuration (nominal capacity of 510 MW) has a minimum load of 40% [11].

Table 5-1 – SES constrained process variables.

Constrained Process Variable	Lower bound	Upper bound
Electrical power output	35% [9]	100%
Firing temperature	816 °C [8]	1,600 °C [7]

5.2. Open-loop configuration

In Figure 5-1, the graphical interface of the dynamic system to be controlled (SES) is shown. It has one input, i.e., the opening of the valve which regulates the natural gas flow rate (u), and two outputs, i.e., the electrical power output (y_1) and the turbine inlet temperature (y_2).

Figure 5-1. Graphical interface of the Dymola model of the SES unit (open loop configuration).

5.3. Closed-loop configuration

In Figure 5-2, the closed-loop configuration is shown, i.e. a PI regulator was added to the model presented in Section 5.2. In addition, since the RG needs the instantaneous value of the state to determine if the imposed set-point variations will violate the constraints, the process variables which constitute the state were collected into a single vector z . As a result, the system has one input, i.e., the electrical power output set-point (v), and two outputs, i.e., the electrical power output (y_1) and the turbine inlet temperature (y_2).

$$x(t + 1) = \hat{A}x(t) + \hat{B}u(t) \quad (20)$$

$$y(t) = \hat{C}x(t) + \hat{D}u(t) \quad (21)$$

Figure 5-3. Representation of poles and zeros for the LTI discrete time closed-loop system (SES + controller).

In Figure 5-3, the eigenvalues of matrix $\hat{A}$ are represented, i.e., the necessary condition on the asymptotic stability of the closed-loop system is verified.

As shown in Eq. (12), in the RG algorithm, a matrix derived from the discrete-time version of the state matrix ($\hat{A}$) is expected to be inverted. This operation is particularly troublesome when traditional controllers are studied. The state-space representation matrices to be used in the RG algorithm refer to the closed-loop system, i.e., both the dynamic system to be controlled and the corresponding feedback regulator. If this regulator is PI-like, then the ensuing closed-loop transfer function will be characterized by a pole in the origin, and the state matrix obtained from the linearization will be singular. From this standpoint, most of the controllers implemented in the present configuration of the IES unit model are PIs. Since the traditional matrix inversion procedure cannot be adopted in the implementation of the RG algorithm, the Moore-Penrose pseudoinverse ($A^\dagger$) approach was followed. The obtained results confirmed the feasibility of this modification to the RG algorithm.

5.4. Design of a dedicated State Observer: Kalman filter

The RG block receives the set-point and the state of the system as inputs, and returns the modified set-point as output. Two cases are considered with an approach developed for each. In the former case, the state variables are assumed to be observable, as mentioned in Section 5.3. A purposefully-defined array collecting the state variables is defined in the “SES” model (Figure 5-4). These variables are then passed to the “State Obs” block which samples the corresponding values every second and calculates the differences with respect to the nominal values ($\delta x = x(t) - x_0$).

Figure 5-4. Final configuration of the closed-loop system ("SES") coupled with the Kalman filter and the RG block ("Ref Gov").

In the latter case, we assume the state variables are not observable. Then we need a means to reconstruct the state of the system starting from the variables that can be adjusted or measured, i.e., $u(t)$ and $y(t)$. It is common practice to use an asymptotically-stable state observer, which permits reconstructing the state of the system starting from the values of the input and output variables. To this end, a Kalman filter was developed and successfully implemented (Figure 5-5). It assumes the state of the system evolves from time (t) to time $(t + 1)$ according to

$$x(t + 1) = \hat{A}x(t) + \hat{B}u(t) + w_Q(t) \quad (22)$$

where $w_Q(k) \sim N(0, Q_k)$ is the process noise which is assumed to be drawn from a zero mean multivariate normal distribution with covariance Q_k . At time $(t + 1)$ a measurement $y(t + 1)$ of the true state $x(t + 1)$ is made according to

$$y(t + 1) = \hat{C}x(t + 1) + \hat{D}u(t) + w_R(t) \quad (23)$$

where $w_R(t) \sim N(0, R_k)$ is the noise which is assumed to be zero mean Gaussian white noise with covariance R_k .

As for the measurement noise covariance (R_k), generally, it is easy to take some off-line sample measurements to determine it, whereas the estimate of the process noise covariance matrix (Q_k) is more difficult as it is not possible to directly observe the process to be controlled. The conceptual steps of the Kalman filter are presented below.

1. *Project the state ahead:* starting from the state estimated at t and the control action performed at the same time-step, the state of the system at next time-step is evaluated by means of the state space representation matrices.

$$\hat{x}^-(t + 1) = \hat{A}\hat{x}(t) + \hat{B}u(t) \quad (24)$$

2. *Project the State Error Covariance matrix ahead:* the State Error Covariance matrix is evaluated at the next time step by adopting the state transition matrix ($\hat{A}$).

$$P^-(t+1) = \hat{A}P(t)\hat{A}^T + Q_k \quad (25)$$

3. Compute the Kalman gain:

$$K(t+1) = P^-(t+1)\hat{C}^T \cdot (\hat{C}P^-(t+1)\hat{C}^T + R_k)^{-1} \quad (26)$$

4. Update State estimate and State Error Covariance matrix: the a priori estimate for the state and the state error covariance matrix are updated thanks to the measure of the output variables.

$$\begin{aligned} \hat{x}(t+1) &= \hat{x}^-(t+1) + K(t+1) \cdot (y(t+1) - \hat{C}\hat{x}^-(t+1)) \\ P(t+1) &= (I - K(t+1)\hat{C}) \cdot P^-(t+1) \end{aligned} \quad (27)$$

Figure 5-5. Graphical representation of the Kalman filter concept.

5.5. Results

5.5.1. Imposed output variables constraints

According to the considerations reported in Section 5.1, dedicated constraints on the system outputs, i.e., the electrical power (y_1) and the turbine inlet temperature (y_2), were defined. In accordance with [8], the minimum allowed load (lower bound for y_1) was set at 10.5 MW (30%). As for the upper bound, we assumed that 5 MW overpower transients are tolerable. The turbine inlet temperature is the highest temperature reached in the Brayton cycle (firing temperature). The gas turbine model shown in Figure 5-1 has a nominal firing temperature of 1,340 °C. In accordance with [7], the value of 1,600 °C was used as upper bound for y_2 . To avoid excessive production of carbon monoxide, the lower bound was set at 816 °C [8]. The constraints are then:

$$10.5 \text{ MW} \leq y_1 \leq 40 \text{ MW} \quad (28)$$

$$816 \text{ °C} \leq y_2 \leq 1,600 \text{ °C} \quad (29)$$

The system constraints were also expressed as a function of the corresponding nominal values ($y_1^{nom} = 35MW$, $y_2^{nom} = 1,340\text{ }^{\circ}C$):

$$-24.5\text{ MW} \leq \delta y_1 \leq +5\text{ MW} \quad (30)$$

$$-524\text{ }^{\circ}C \leq \delta y_2 \leq +260\text{ }^{\circ}C \quad (31)$$

5.5.2. Simulation outcomes

The SES object-oriented model responses with and without the coupling with the RG block are shown in Figure 5-6. The system is perturbed by a ramp-like variation of the controlled variable set-point (y_1^{set}), i.e., electrical power is increased by 10 MW between $t = 30\text{ s}$ and $t = 50\text{ s}$. The RG block ensures that the system output is in the admissible range ($y_1 \leq 40MW$). The dynamic response of the system subjected to a saw-tooth input with a period of 20 seconds and an amplitude of 10 MW is shown in Figure 5-7.

Figure 5-6. Closed-loop power response (ramp set-point signal).

Figure 5-7. Closed-loop power response (saw-tooth set-point signal).

Performed simulations showed that the constraints on y_1 are more limiting than the ones on y_2 . In other words, for all ranges of power output considered, the constraint on the firing temperature was automatically satisfied. To show this effect, the constraint on y_1 was relaxed, and an even more limited range of variation was granted to y_2 :

$$y_2)_{max} = y_2^{nom} + 100\text{ }^{\circ}C \quad (32)$$

The dynamic response of δy_2 resulting from a saw-tooth input with an amplitude of 20 MW and a time period of 10 seconds is shown in Figure 5-8. In particular, it can be observed that the added component ensures the compliance with the constraint on the turbine inlet temperature (y_2), i.e., the firing temperature never exceeds the upper limit.

Figure 5-8. Closed-loop temperature response (saw-tooth set-point signal).

6 BALANCE OF PLANT (BOP)

6.1. Definition of process variable constraints

The minimum requirements for the maneuverability capabilities of modern Generation III/III+ reactors are defined by the utility requirements, which are based on the requirements of the grid operators. According to the current version of the European Utility Requirements (EUR), nuclear units must be capable of a minimum daily load cycling operation between 50% and 100% of their nominal power output [13].

In a steam turbine, the erosion of intermediate and low-pressure blades is usually caused by the presence of water droplets in the steam flow rate. Operation below design inlet steam temperature or at low load can cause condensation in these final stages, leading to erosion issues. In the Rankine cycle, the steam is expanded to low pressures reached in the condenser. The cycle efficiency is strongly affected by exhaust steam quality. A decrease in the condenser pressure results in higher power output and lower steam quality, and vice versa. However, as exhaust steam quality declines, the potential for blade damage in the lower pressure stages gets higher. In PWRs, the steam moisture at the LP turbine outlet is about 90.7% [14]. Stress corrosion cracking of steam turbines mainly occurs at locations where the steam moisture is 3-4%. A limit to the steam quality at turbine exhaust to avoid erosion of turbine blades is 0.88 [15].

Table 6-1 – BOP constrained process variables.

Constrained Process Variable	Lower bound	Upper bound
Electrical power output	50% [13]	100% [13]
Steam quality at the turbine outlet	0.88 [15]	1.0

6.2. Open-loop configuration

In Figure 6-1, the graphical interface of the dynamic system to be controlled, i.e., the Energy Manifold (EM) coupled with the Balance of Plant (BOP) is shown. With respect to the version contained in the repository, the configuration of the studied system was simplified a bit, i.e., few components who do not play a relevant role in defining the system governing dynamics were removed.

The synchronized operation of the components downstream to the EM, i.e. the BOP and the Industrial Process (IP), is performed by operating the TDV, the BPDV, and the IPDV valves. The rate power output of the overall BOP is equal to 413.285 MW. The steam flow rate coming from the EM is subdivided into eight flows heading towards the same number of steam turbines ($nFlow_down$). These turbines are identical, and it is assumed that the same controller is used to operate them all. For this reason, when the BOP electrical power is mentioned, the output of the single turbine will be meant.

The closed-loop system has one input, i.e., the opening of the TDV valve which regulates the steam flow rate to the turbine (u), and two outputs, i.e., the electrical power output (y_1) and the steam turbine HP stage inlet pressure (y_2).

Figure 6-1. Graphical representation of the Dymola model of the EM coupled with the BOP system (*open loop* configuration).

6.3. Closed-loop configuration

In Figure 6-2, the closed-loop configuration is shown. Two feedback control schemes to operate the TDV valve and the BPDV valve were added to the open-loop model displayed in Figure 6-1. In particular, the BOP electrical power output is controlled by adjusting the TDV valve opening by means of a PI controller. Both the measured variable and the imposed set-point signals pass through a preliminary filter first and, eventually, the PI controller-evaluated control action is summed with a reference value. At the same time, a parallel regulator based on an algebraic feedback scheme is governing the BPDV valve opening. Starting from the instantaneous value of the TDV opening,

the BPDV valve opening is derived. The implemented scheme is such that when the TDV valve is opened the BPDV valve is closed and vice versa. In this way, the consequences of overpressure and depressurization scenarios can be limited.

The closed-loop system has one input, i.e., the BOP electrical power output set-point (v), and two outputs, i.e., the actual BOP electrical power output (y_1) and the steam turbine HP stage inlet pressure (y_2). Unlike the first approach developed for the operation of the SES, the process variables which constitute the dynamic state of the system are not collected. The experience gained proved that the Kalman filter can provide a sufficiently accurate estimate of the unobserved variables. Therefore, thanks to the adoption of the Kalman filter, the state of the system will be retrieved starting from the values of the input and output variables only.

Figure 6-2. Graphical representation of the Dymola model of the EM coupled with the BOP and the corresponding control system (closed loop configuration).

Figure 6-3. Final configuration of the closed-loop system ("EM+BOP") coupled with the Kalman filter and the RG block ("Ref Gov").

Figure 6-4. Simulation outcomes of the performed operational transient.

Because of the level of coupling of the two systems (EM and BOP) and the features of the adopted regulators, the dynamics of the present system is expected to be characterized by a more nonlinear behavior than the SES. To this aim, a preliminary operational transient was simulated, i.e., a reduction of the electrical power output equal to 40% of the rated value. In Figure 6-4, the corresponding simulation outcomes are presented. First of all, the evolution of the volumetric flow rate was considered. This variable is strongly related to the speed triangles, which need to be

preserved during the operation of a steam turbine. As shown in Figure 6-4b, the evolution of this variable is barely affected during the simulated power transient. On the other hand, the evolution of the steam pressure at the turbine inlet (Figure 6-4c) is quite concerning, i.e., the power reduction caused a 20 bar pressure drop which means significant mechanical stress to the BOP components. Traditionally, when the electrical power is modulated, the operating points of a Rankine power cycle are preserved, and the flow rate is adjusted. The results show that the specific enthalpy drop across the turbine (Figure 6-4d) changes by only 6% during the transient, and the steam quality at the turbine outlet (Figure 6-4e) is not greatly affected. At the same time, since no dedicated controller was foreseen, the steam temperature at the turbine inlet (Figure 6-4f) is not constrained, and it drops by 25 °C.

6.4. Derivation of the state-space representation matrices

Unlike the SES, the control system of the coupled system constituted by the EM and the BOP is highly nonlinear. The SES system was controlled by means of a single PI controller, i.e., a linear controller was coupled to a system whose dynamics was not characterized by relevant nonlinearities. On the other hand, because of the coupling between the BOP and the EM along with the peculiar features of the adopted control system, the Dymola linear analysis tools cannot be used to derive a state-space representation of the resulting closed-loop system. For this reason, a different approach was followed. The needed LTI model was derived by adopting the MATLAB System Identification Toolbox [16], which implements the subspace algorithm for the identification procedure. First, a dynamic transient was simulated, i.e., the electrical power set-point (v) was perturbed by imposing a 5 MW ramp-like drop. Then, starting from the input and the output signals, a suitable best-estimate model was derived. The obtained LTI time-continuous model is asymptotically-stable since the state matrix eigenvalues (λ_i) meet the necessary stability condition (Eq. (33)).

$$|\lambda_i| < 1 \quad i = 1, \dots, n \quad (33)$$

$$\lambda_i = \{0.7148, 0.995 \pm 0.0046i, 0.999\} \quad (34)$$

In Figure 6-6, the LTI model predictions were compared against the reference Dymola model responses. In particular, different amplitude set-point trajectories were fed to the closed-loop system. Not surprisingly, the simulation outcomes show that the accuracy of the LTI model predictions drops as the amplitude of the imposed set-point variations increases. In addition, it is interesting to observe that the Dymola model-simulated transients are characterized by very different time constants. Conversely, the responses of the LTI model are governed by the same time constant, i.e., for reduced amplitude transients the LTI response is faster than the Dymola model one, for large amplitude transients the LTI response is much slower than the Dymola model one.

Figure 6-5. Representation of poles and zeros for the LTI discrete time closed-loop system (BOP + EM + controller).

In Figure 6-5, the eigenvalues of matrix $\hat{A}$ are represented, i.e., the necessary condition on the asymptotic stability of the closed-loop system is verified.

The adoption of an identification method has consequences. If a model-based approach is used, the needed LTI model will be derived by linearizing a set of first principle equations around a reference equilibrium point. In this case, the variables which constitute the state vector have physical meaning. On the other hand, if a data-driven approach is used, the needed LTI model will be derived starting from the power and pressure dynamic responses along with the set-point signal that triggered the transient. In this case, the relationship between input and output variables is accurately represented, but the variables which constitute the state vector have no physical meaning. It follows that it is not possible to monitor their evolution by looking at the Dymola model. A dedicated state observer like the previously adopted Kalman filter is needed to retrieve the dynamic responses of those variables and to permit the operation of the RG block.

(a)

Figure 6-6. Results of the performed system identification. The solid blue curves represent the LTI model responses, the dashed red lines the Dymola model ones.

6.5. Results

6.5.1. Imposed output variables constraints

As mentioned in Section 6.1, the safe operation of a steam turbine requires that certain limits on the values assumed by the electrical power output and by the water content in the exhaust steam flow rate are represented. On the other hand, the simulation outcomes showed that the value of the steam quality at the turbine outlet is very low, even at nominal conditions. To this aim, in addition to the electrical power output constraints, a further set of limits was imposed on the values of the steam pressure at the turbine inlet. The constraints are then:

$$25.78 \text{ MW} \leq y_1 \leq 54.14 \text{ MW} \quad (35)$$

$$45.16 \text{ bar} \leq y_2 \leq 60.16 \text{ bar} \quad (36)$$

The system constraints can also be expressed as a function of the corresponding nominal values ($y_1^{nom} = 51.56 \text{ MW}$, $y_2^{nom} = 55.15 \text{ bar}$):

$$-25.78 \text{ MW} \leq \delta y_1 \leq +2.578 \text{ MW} \quad (37)$$

$$-10 \text{ bar} \leq \delta y_2 \leq +5 \text{ bar} \quad (38)$$

6.5.2. Simulation outcomes

To test the capabilities of the developed RG scheme, different constraints with respect to the ones expressed in Eqs. (35)(36) were imposed on y_1 and y_2 . The goal was to prove that the developed control scheme can simultaneously handle constraints on different process variables. To this aim, the same operational transient (a 20 MW ramp-like power drop) was simulated by imposing two different set of constraints. In the former scenario, a more restrictive constraint was imposed on the electrical power output, whereas the one limiting the pressure was relaxed (Eqs. (39)(40)).

$$y_{1,min} = y_1^{nom} - 10 \text{ MW} \quad (39)$$

$$y_{2,min} = y_2^{nom} - 20 \text{ bar} \quad (40)$$

Figure 6-7. Operational transient. The most constraining limit is the imposed on the electrical power output (y_1).

In the latter scenario, a more restrictive constraint was imposed on the pressure, whereas the one limiting the electrical power output was relaxed (Eqs. (41)(42)).

$$y_1)_{min} = y_1^{nom} - 25.78 \text{ MW} \quad (41)$$

$$y_2)_{min} = y_2^{nom} - 5 \text{ bar} \quad (42)$$

One of the most important outcomes of these simulated transients is that they proved the feasibility of the developed methodology. In the case of the EM+BOP coupled system, since the linearization by means of the Dymola linear analysis tools was not possible, an identification approach was used to derive a simplified LTI model to predict the system response. From this standpoint, this opens up interesting modeling prospects. In particular, these results proved that it is not necessary to adopt a model-based approach to derive the needed LTI model, but any effective description of the system dynamics might work just fine. In this work, the MATLAB System Identification Toolbox was used to derive the state-space representation model of the studied system but, in the future applications, other data-driven approaches could be used. From this standpoint, because of its capability of generating surrogate models which can mimic the dynamics of the complicate dynamic systems, RAVEN can be adopted.

Figure 6-8. Operational transient. The most constraining limit is the imposed on the turbine inlet pressure (y_2).

7 HIGH-TEMPERATURE STEAM ELECTROLYSIS PLANT (HTSE)

7.1. Description of the plant configuration

The High-Temperature Steam Electrolysis (HTSE) plant utilizes a combination of thermal energy and electricity to split water into hydrogen (H_2) and oxygen (O_2). A mixture of hydrogen and steam at 850°C is supplied to the cathode side of the solid structure where it is reduced into hydrogen, releasing oxide ions in the process. The steam conditions are typical of LWR technology with a temperature of 318°C and a pressure of 5.8 MPa. To reach the nominal operating temperature (850°C), additional heat is provided by an Electric Topping Heater (ETH). The outlet anode stream is an oxygen-enriched air and exits from the system at 750°C . As shown in Figure 7-1, the HTSE plant uses a minor fraction of the thermal power produced by the nuclear reactor. At nominal operating conditions, the HTSE process uses an electrical load input of 51.1 MW_e , of which 5.61 MW_e is used in the ETHs. The remainder is directed to the Solid Oxide Electrolysis Cell (SOEC) stacks for electrolysis. A thermal energy of 18.5 MW_{th} from the nuclear reactor is used to convert the feedwater to low-temperature steam and heat the air that is used as sweep gas.

Figure 7-1. Graphical representation of the BOP and IP power consumptions

The steam utilization (SU) factor is defined as the percentage of the total inlet stream flow rate that is consumed by the electrolysis reaction. The nominal value of the cathode stream flow (4.48 kg/s) is selected to obtain a nominal SU factor of 80%. The nominal value of the anode stream flow rate (23.3 kg/s) is selected to achieve the cathode stream outlet temperature of 750 °C. At nominal conditions, the system produces 0.401 kg/s of hydrogen.

As for the system operation, two different control strategy (“Power control” and “Steam flow control”) are envisioned. They are shown in Figure 7-2 and in Figure 7-3.

With respect to Figure 7-2, cathode temperature at the HX stack outlet (y_1) is controlled by adjusting the absorbed electrical (u_1), the anode temperature at the stack outlet (y_2) is controlled by governing the opening of “TCV_anode” valve (u_2). In both cases, PID feedback controllers are adopted. On the other hand, the opening of “TCV_cathode” valve (u_3) is constant.

With respect to Figure 7-3, cathode temperature at the HX stack outlet (y_1) is controlled by adjusting the opening of “TCV_cathode” valve (u_3), the anode temperature at the stack outlet (y_2) is controlled by adjusting the opening of “TCV_anode” valve (u_2). In both cases, PID feedback controllers are adopted. The amount of absorbed electrical power (u_1) is not derived by a PID controller but it is imposed by RAVEN. At the interface of the system, a dedicated limiter ensures that the input power does not exceed the design limits.

Figure 7-2. Dymola model of the HTSE plant. Pairings among input and output variables are represented ("Power control" strategy).

Figure 7-3. Dymola model of the HTSE plant. Pairings among input and output variables are represented ("Steam flow control" strategy).

In both the control strategies, two regulators are modeled in the SOEC stack (Figure 7-4). The cathode temperature at the SOEC stack outlet is controlled by adjusting the mass flow rate of the anode stream. The mole fraction of the cathode H₂ stream at the SOEC stack inlet and the SU factor are both controlled by a single controller. Starting from the desired values for the inlet H₂ mole fraction in the hydrogen-steam mixture and the SU factor, the desired cathode stream inlet flow rate can be calculated as a function of the measured cathode stream outlet flow rate. Numerous feedback/feedforward controllers were implemented to maintain the desired process conditions. The controllers with their corresponding set-point values are listed in Table 7-1.

Figure 7-4. Dymola model of the SOEC stack.

Table 7-1 – HTSE control scheme components (derived from [17][18]).

Controller type	Controlled variable	Reference value	Control action
Feedback (PI)	Cathode stream temperature at the cathode HX outlet	283.4 °C	Electric power (“Power control”), Cathode gas valve (“Steam flow control”)
Feedback (PI)	Anode stream temperature at the anode HX stack outlet	259 °C	Anode gas valve
Feedback (PI)	Cathode stream temperature at the SOEC stack outlet	750 °C	Anode gas mass flow
Feedback (PI)	Cathode stream H ₂ mole fraction at the SOEC stack inlet	0.1	Cathode gas mass flow
Cascade (feedforward/feedback [PI])	SU factor	80 %	Cathode gas mass flow

In conclusion, the two presented different control strategies differ in how the cathode stream temperature is controlled, and the role of the absorbed electrical power. The RG algorithm might

play an important role if it was implemented in the control scheme corresponding to the “Steam flow control” strategy. The amount of the absorbed electrical power is externally imposed by RAVEN, and it might happen that during operational transients it might cause the constrained temperature to exceed the design limits. To this aim, the RG layer might be adopted to prevent dangerous temperature transients ensuing from the imposed RAVEN values.

7.2. Imposed variable constraints

To prevent the fracture of delicate SOEC stack components during dynamic operation, significant thermal excursions in the stack should be avoided. Previous work indicated that the maximum allowable temperature difference along a 0.1 m cell is 100 °C, corresponding to 10 °C/cm [18]. A nominal SU factor of 80% is used, despite theoretically it can be increased till 100%. A higher SU factor corresponds to a higher H₂ production (i.e., higher electrolysis efficiency). However, it is not desirable to run the electrolyzer to 100% because localized steam starvation might occur, thus severely degrading performance. However, previous work does not show maximum and minimum allowed values during transients. It derives that the SU factor should be adequately maintained close to its nominal value at different operating conditions. This is accomplished by adjusting the feedwater flow rate, thereby regulating the cathode stream flow rate at the SEOC stack inlet.

Table 7-2 – HTSE constrained process variables.

Constrained Process Variable	Lower bound	Upper bound
Temperature gradient across the SOEC cell	-	10 °C/cm [18]
SU factor	-	< 100% [18]

7.3. Open-loop configuration

A case study was conducted to analyze the dynamic performance of the HTSE plant when it is operated according to the “Steam flow control” strategy. Despite the system includes an *ad-hoc* limiter that ensures that the power is above or below a threshold, a set of simulations were conducted to verify that the currently implemented regulators can maintain the constrained process variables within the design limits. The open-loop response of the system was analyzed by imposing three different power consumption input signals to monitor the behavior of the variables subjected to constraints.

1. Step function: from rate level (51.1 MW), the power is reduced by 30 MW at t=1,000 s (step function)
2. Saw-tooth function, starting at t=500 s, with an amplitude of 30 MW and a period of 5 minutes;

3. Saw-tooth function, starting at $t=500$ s, with an amplitude of 30 MW and a period of 10 minutes;

The dynamic responses of the system are shown in Figure 7-5, Figure 7-6 and Figure 7-7. In all the simulations, the temperature gradient was kept lower than the upper design limit ($10^{\circ}\text{C}/\text{cm}$), indicating that the stack was safely operated during the simulated transients. In all cases, the SU factor controller got to maintain the value of SU factor close to the nominal value (80%). These results show that the controllers that were implemented in the model could maintain the constrained process variables within the safety limits. Therefore, in the current operating conditions, there is no need to implement additional filters or add a RG block to pre-filer RAVEN-imposed inputs. This analysis shows that the HTSE plant can maintain all the critical variables close to the corresponding set-points regardless of the time-varying electrical load absorbed by the plant.

Figure 7-5. Step response. Power consumption of the HTSE plant (a); Electrolyzer solid structure temperature gradient (b); SU factor (c).

Figure 7-6. Saw-tooth response (5 min period). Power consumption of the HTSE plant (a); Electrolyzer solid structure temperature gradient (b); SU factor (c).

Figure 7-7. Saw-tooth response (10 min period). Power consumption of the HTSE plant (a); Electrolyzer solid structure temperature gradient (b); SU factor (c).

8 CONCLUSIONS

Equipment operating limitations in an IES can be formally met through a control system design procedure known as the Reference Governor. The approach augments the existing controllers in a plant unit with an advance controller that modifies the issued set-points so that selected process variables remain within limits. The design procedure was applied to the reference multi-unit system that has been the focus of Modeling and Simulation task in the IES program. Results describing application to the problem of limiting key process variables during operational transients for two of the plant units, the balance of plant and the gas turbine, were then presented. It was demonstrated that the Reference Governor-based approach is an effective means for ensuring equipment operating constraints can be met in an IES. The software that implements the method has been made accessible to others on the Modeling and Simulation upload site.

9 NOMENCLATURE

Roman Symbols

A	State matrix
B	Input matrix
C	Output matrix
D	Feedthrough matrix
H_x	Matrix of constraints on state variables
H_v	Matrix of constraints on output variables
$K(t)$	Kalman gain
K_P	PI controller (P gain)
$\tilde{O}_\infty$	Maximal output admissible set
P	Admissible range of variation of output and state variables
$P(t)$	State error covariance matrix
Q_k	Covariance of the process noise
$r(t)$	RAVEN-provided set-point
R_k	Covariance of the measurement noise
T	Transformation matrix used to obtain the dynamic system balanced representation

$x(t)$	State vector (plant and controller)
$\hat{x}(t)$	Estimated state vector (plant and controller)
$y(t)$	Output vector
Y	Polytope describing the admissible range of output variables

Greek Symbols

β	Scalar adjustable parameter optimized by the RG algorithm
λ	State matrix eigenvalues

Superscripts

†	Moore-Penrose pseudoinverse matrix
T	Transposed matrix

Subscripts

0	Reference value
-----	-----------------

$u(t)$	Input vector	min	Minimum value
$v(t)$	RG-adjusted set-point	Q	Process
w	Noise	R	Measurement

10 REFERENCES

- [1] W. Shyy, M.P. Ebert, "Heat Transfer and Fluid Flow in Rotating Sealed Cavities," *Advances in Heat Transfer*, 35, pp. 173-248, 2001.
- [2] E. Garone, S. Di Cairano, I. Kolmanovsky, "Reference and command governors for systems with constraints: A survey on theory and applications," *Automatica*, 75, 306-328, 2017.
- [3] A. Bemporad, E. Mosca, "Constraint fulfilment in Control Systems via predictive reference management," *Proceedings of the 33rd Conference on Decision and Control*, 3017-3022, Lake Buena Vista, FL, 1994.
- [4] I. V. Kolmanovsky, E. Garrone, S. Di Cairano, "Reference and command governors: a tutorial on their theory and automotive applications," *Proceedings of 2014 ACC*, Portland, OR, June 4-6, 2014.
- [5] E. G. Gilbert, I. V. Kolmanovsky, "Fast reference governors for systems with state and control constraints and disturbance inputs," *International Journal of Robust and Nonlinear Control*, 9(15), pp. 1117-1141, 1999.
- [6] A.W. James, S. Rajagopalan, "Gas turbines: operating conditions, components and material requirements," *Structural Alloys for Power Plants*, pp. 3-21, 2014.
- [7] Mitsubishi Heavy Industries, available at <https://www.mhi.com/news/story/1105261435.html>. Accessed on 1/29/2019.
- [8] R. Pavri, G.D. Moore, "Gas Turbine Emission and Control". GE Power Systems, technical report GER-4211.
- [9] GE Power, "7E Power Plants". Available at https://www.ge.com/content/dam/gepower-pgdp/global/en_US/documents/product/gas%20turbines/Fact%20Sheet/2018-prod-specs/7E-power-plants.pdf.
- [10] GE Power, "7F Heavy Duty Power Plants". Available at https://www.ge.com/content/dam/gepower-pgdp/global/en_US/documents/product/gas%20turbines/Fact%20Sheet/2017-prod-specs/7f-power-plants.pdf.
- [11] GE Power and Water, "9HA.01/02 Gas Turbine". Available at https://www.ge.com/content/dam/gepower-pgdp/global/en_US/documents/product/gas%20turbines/Fact%20Sheet/9ha-fact-sheet-oct15.pdf.
- [12] A.J. Laub, M.T. Heath, C.C. Paige, R.C. Ward, "Computation of system balancing transformations and other applications of simultaneous diagonalization algorithms," *IEEE Transaction on Automatic Control*, AC-32(2), pp. 115-122, 1987.
- [13] A. Lokhov, "Load-following with nuclear power plants", *NEA News* 2011, No. 29.2, pp. 18-20, 2011.
- [14] S. Zhou, A. Turnbull, "Steam Turbine Operating Conditions, Chemistry of Condensates, and Environment Assisted Cracking - A Critical Review", *NPL Report MATC (A) 95*, 2002.
- [15] O. Singh, "Applied Thermodynamics", *New Age International*, pp. 399-400, 2003.
- [16] The MathWorks, Inc., "System Identification Toolbox™ User's Guide", 2015.
- [17] J.S. Kim, M. McKellar, S.M. Bragg-Sitton, R.D. Boardman, "Status on the Component Models Developed in the Modelica Framework: High-Temperature Steam Electrolysis Plant & Gas Turbine Power Plant," *INL/EXT-16-40305*, October 2016.
- [18] J.S. Kim, R.D. Boardman, S.M. Bragg-Sitton, "Dynamic performance analysis of a high-temperature steam electrolysis plant integrated within nuclear-renewable hybrid energy systems," *Applied Energy*, 228, pp.2090-2110, 2018.

Nuclear Science and Engineering (NSE) Division

Argonne National Laboratory
9700 South Cass Avenue, Bldg. 208
Argonne, IL 60439

www.anl.gov

Argonne National Laboratory is a U.S. Department of Energy
laboratory managed by UChicago Argonne, LLC